Modeling and Simulation of Visual Impairment and Intracranial Pressure (VIIP) in Space

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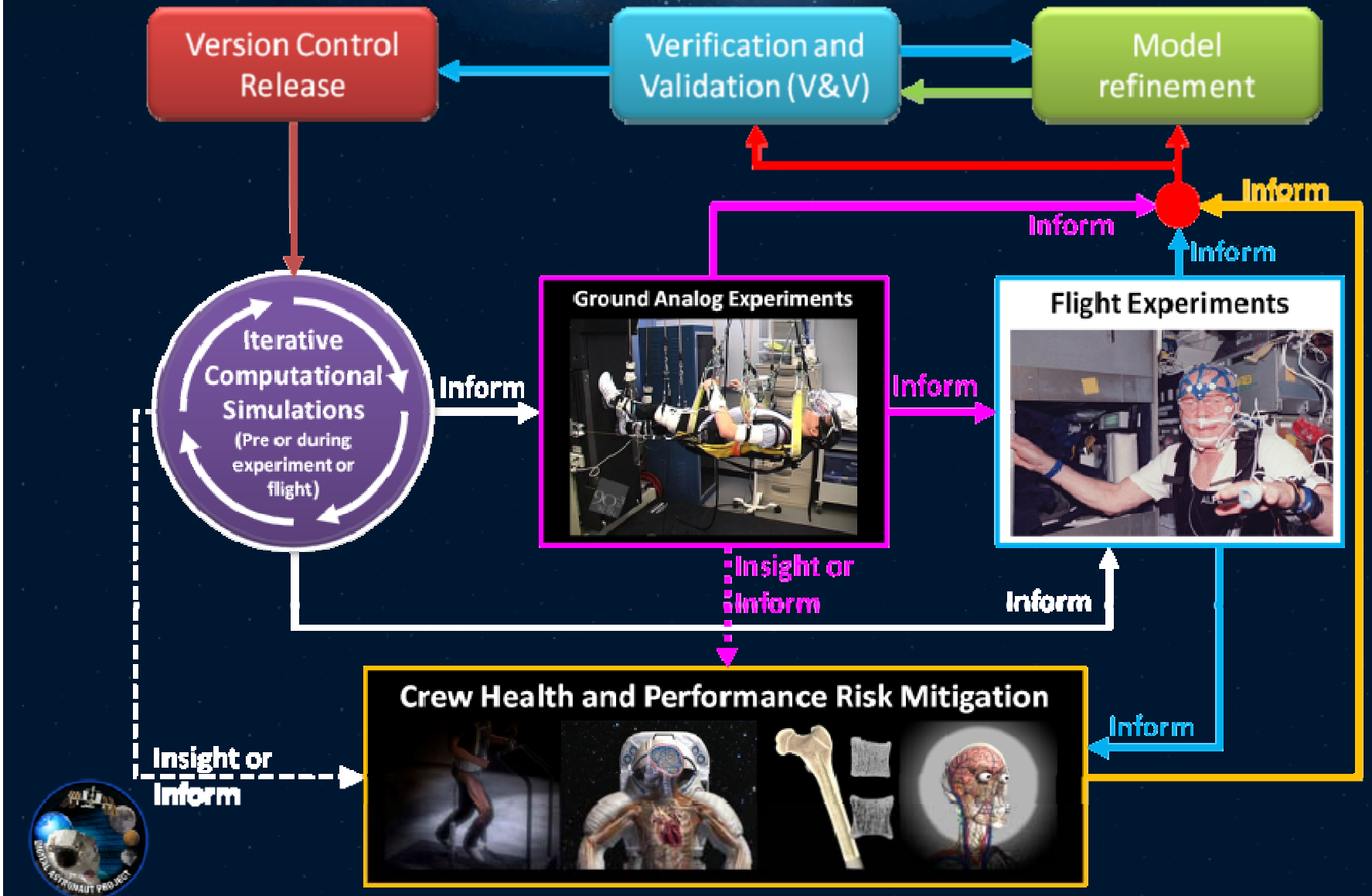
Overview

- Value of modeling and simulation (M&S) for biomedical research and operations
- Background of visual impairment and intracranial pressure (VIIP) due to spaceflight
- Causal factors in VIIP biomechanical pathways
- Proposed approaches on how M&S can be leveraged to understand VIIP

Introduction

- Mars and NEO missions will expose astronauts to extended durations of reduced-gravity, isolation and higher radiation
- These new operational conditions pose health risks that are not well understood and may not be anticipated
- Advanced computational simulation environments can beneficially augment research to predict, assess and mitigate potential hazards to astronaut health
- The NASA Digital Astronaut Project (DAP) within the NASA Human Research Program (HRP) strives to achieve this goal

Value of Modeling and Simulation for Space Biomedical Research and Operations

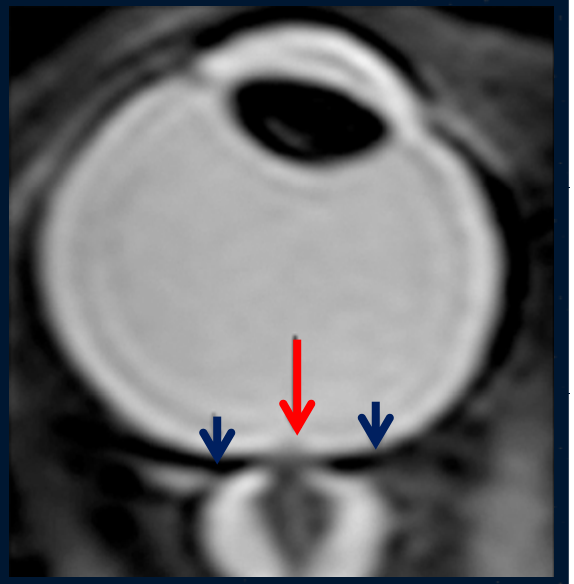


Spaceflight Induced Ophthalmic and ICP Changes

Some astronauts in short- and long-duration spaceflight report a change in visual acuity (29%/60%) -Mader et al. (2011)

Persisting Changes After ~6 Months in Space	Total affected out of 34 US Astronauts
Optic nerve sheath distension	6/8 (75%)
Optic disc edema	5/8 (62.5%)
Posterior globe flattening	5/8 (62.5%)
Choroidal folds	4/8 (50%)
Elevated post-flight CSF pressure	4/8 (50%)
Cotton wool spots	3/8 (37.5%)
Decreased IOP post-flight	3/8 (37.5%)

POST-FLIGHT IMAGE



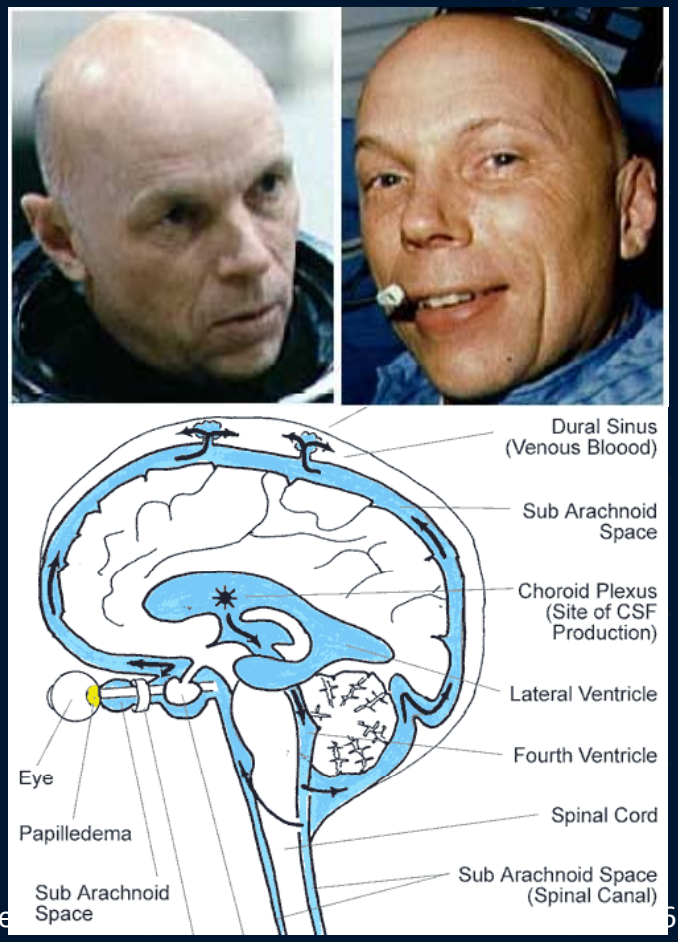
PRE/IN/POST-FLIGHT IMAGING

Potential Causal Factors in VIIP

The causal chain linking microgravity and VIIP is at present unknown, but key factors include:

- Cephalad fluid shift
- Hydrodynamic forces governed by intracranial pressure (ICP) and blood/Cerebrospinal fluid (CSF) flow in the cranial vault
- Quasi-static and dynamic biomechanical responses of the corneo-retino-scleral shell, the optic nerve head (ONH) and its surrounding tissues to changes in ICP, Intraocular pressure (IOP) and fluid flow; and
- Tissue properties such as peripapillary sclera deformation and remodeling characteristics

CEPHALAD FLUID SHIFT



Potential Causal Factors in VIIP (Cont'd)

- Acute ICP and IOP changes during exercise, e.g., valsalva maneuver (VM)
  - VM during resistive exercise is known to spike ICP and IOP (Haykowsky et al., 2003; Bakke et al., 2009)

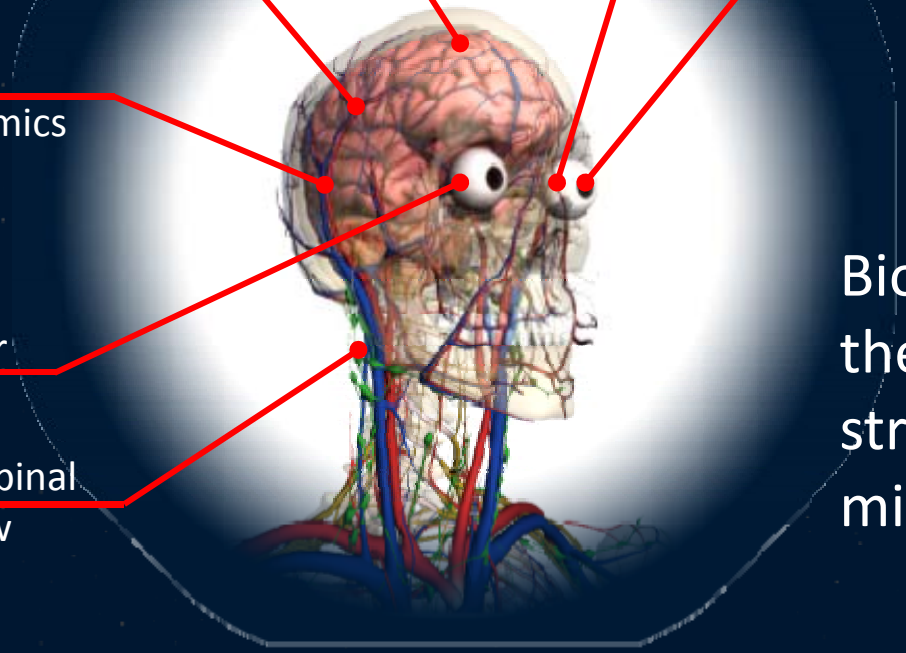
Research/Risk Knowledge Gaps Most Amenable to Computational Modeling

- **VIIP6:** How do changes in vascular compliance/ pressures influence intraocular pressure (IOP) or intracranial pressure (ICP)?

- **Gap VIIP2:** Does exposure to microgravity cause changes in visual acuity, IOP and/or ICP? Are the effects related to mission duration?

- **Gap VIIP4:** Are changes in visual acuity related to changes in:
  1) deformation of the ONH;
  2) chronic choroidal engorgement;
  3) elevated IOP; and/or
  4) ICP?

Focus Area for Modeling and Simulation of VIIP



Biomechanical responses of the intracranial and ocular structure due to exposure to microgravity

(Adapted from Google Body – http://bodybrowser.googlelabs.com)

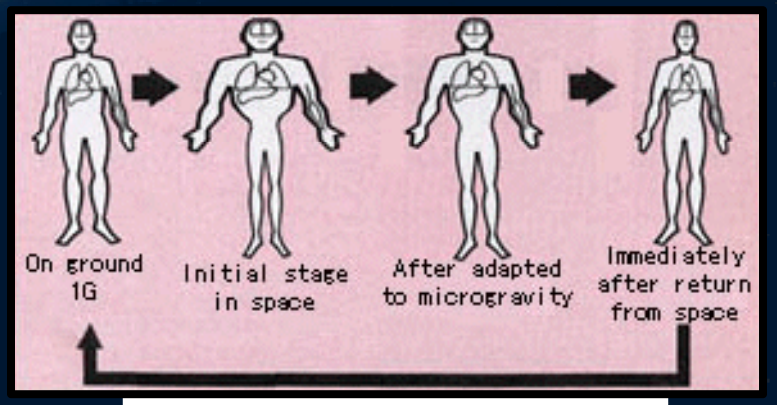
Proposed M&S Approaches

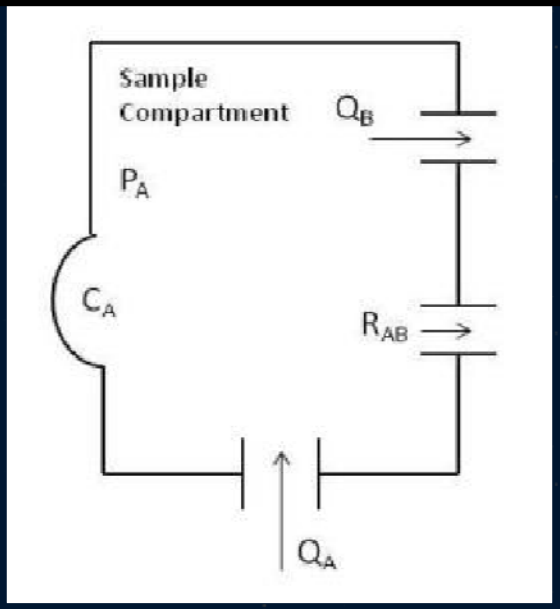
- Lumped parameter models of the intracranial and spinal compartments
- Finite element model of the eye
- Computational fluid dynamics of the intracranial and spinal space
- High fidelity tissue models to capture nonlinear/viscoelastic properties
- Integrate multiple models for systems analyses
- Leverage external collaborations for critical expertise in these areas

Lumped Parameter Model

- "Simplified" whole-body model to capture time-dependent pressure/flow in subarachnoid space (SAS) posterior to the eye
  - Involves blood and CSF flow
  - Model includes both fluid shift and heartbeat-dependent fluctuations

CEPHALAD FLUID SHIFT

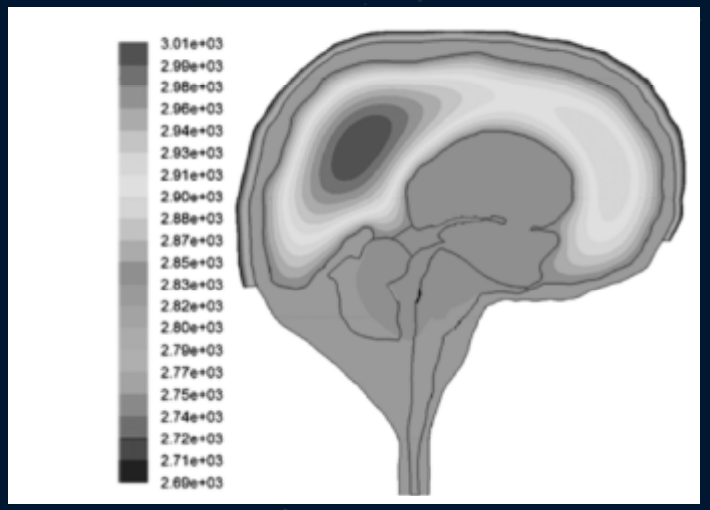




LUMPED COMPARTMENT USED FOR BLOOD/CSF FLOW

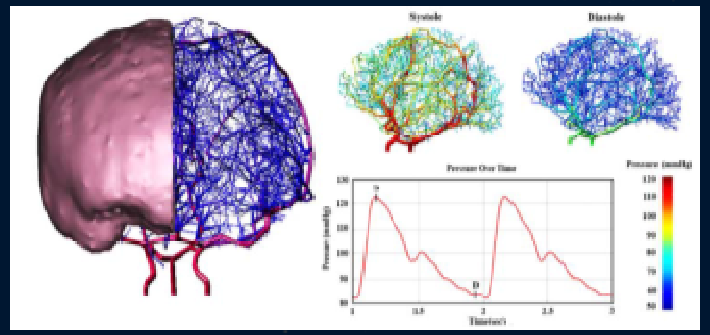
CFD Modeling of the Spinal and Intracranial Compartments

- 2D and 3D computational fluid dynamic modeling for high fidelity prediction of the CSF flow within the spinal and intracranial SAS



(Linninger *et al.,* 2007)

- High fidelity modeling of cerebral vascular network and hemodynamics

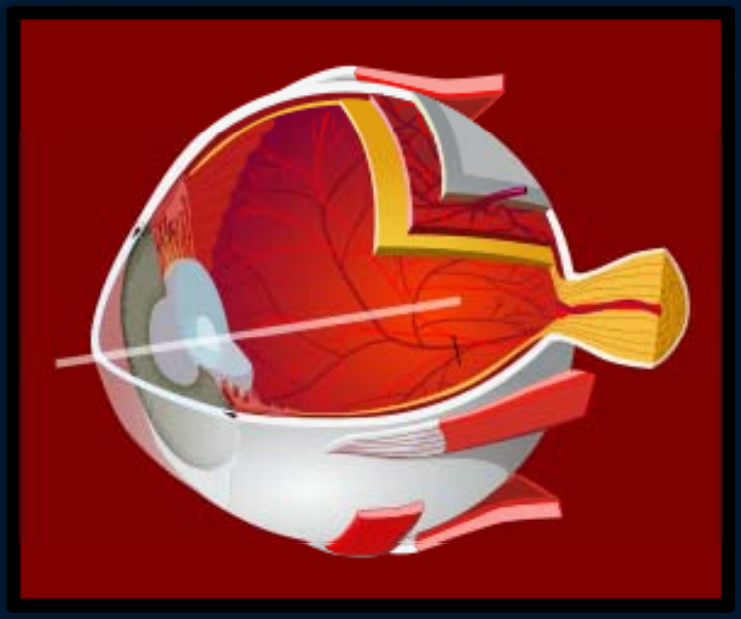


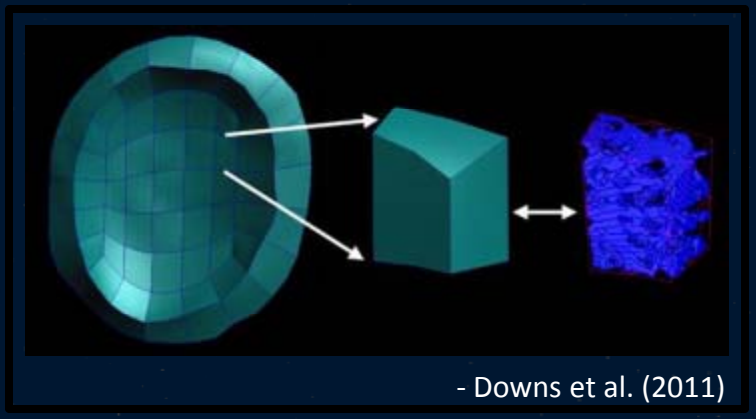
(Vaičaitis *et al.* 2011)

Finite Element Model of the Eye and ON

- Idealized geometry includes corneo/scleral shell, choroid layer and retina, ONH, retrobulbar SAS

- Coupled with lumped parameter or CFD model to investigate fluid/structure interaction driven by applied pressure at base of retrobulbar SAS



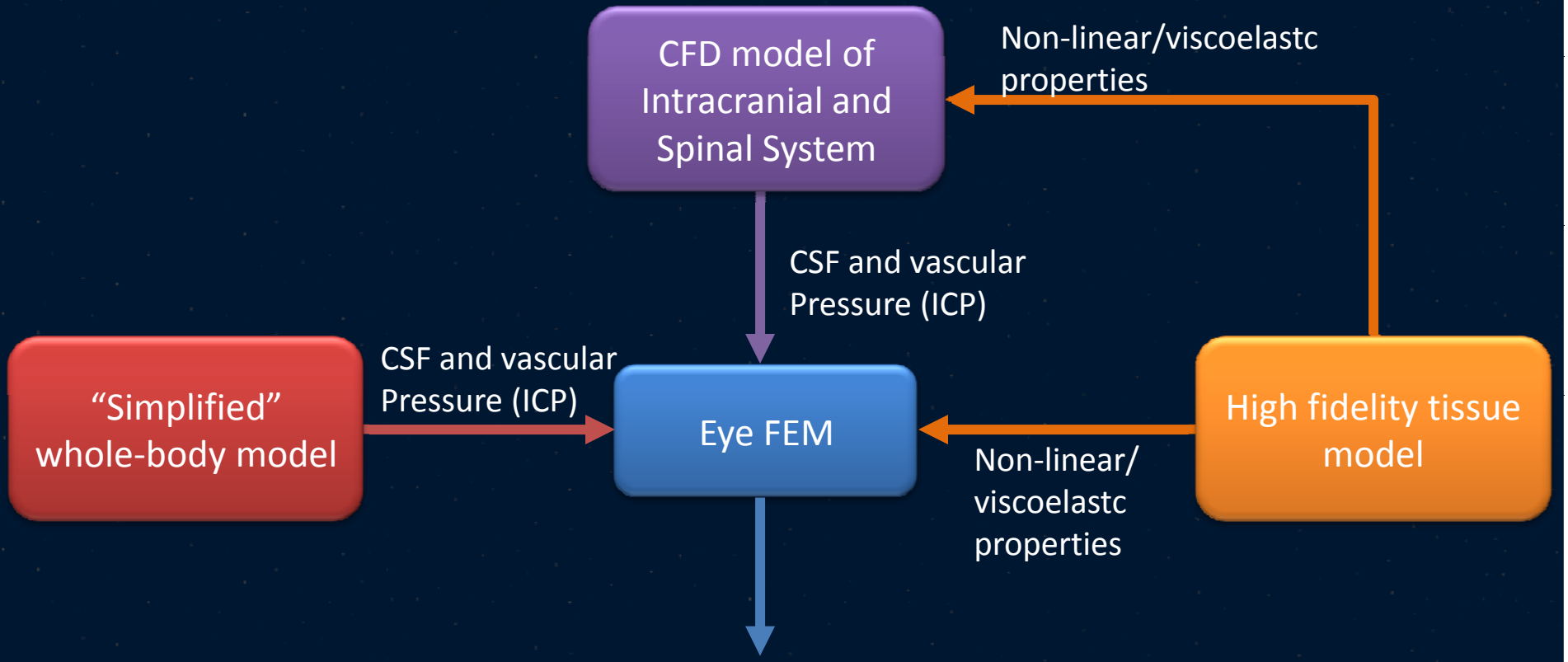


- Downs et al. (2011)

High Fidelity Tissue Modeling

- Eye tissue stiffness increases at high strain rates (Elsheikh et al., 2007) - e.g. during VM
- Tissue stiffness increases with age (Albon et al., 2000; Elsheikh et al., 2007)
  - The affected crew's mean age was 50.2 $\pm$ 4.2 years (Mader et al., 2011)
- Hypothesized remodeling of the ocular and vascular structures due to chronic elevated pressure in the cranial space (Mader et al., 2011; Wu et al., 2005)
- High fidelity tissue model that can be integrated with FE and CFD models, such as the approach proposed by Grytz and Meschke (2008 &2009), will be necessary to accurately capture the modeling and remodeling process of ocular and intracranial tissues

Integrated Systems Analysis



Infusion of External Efforts

- 2-Years: Measurement of ICP and IOP
  - Acute: Short-duration tilt tests
  - Chronic: Tracking adaptation of ICP and IOP
- 5- Years: Acute/Chronic Changes in the Material and Adaptive Properties
  - Substantial information exists on microgravity's influence on vascular networks
  - Little space flight data on eye, optic nerve and CSF network
  - Identify – what are the unique and sensitive parameters that influence individual susceptibility?
- >5-Years: High Fidelity Validation Data
  - Statistically significant comparative measures to validate predictions
    - Unlikely this will be space flight population – What is an appropriate ground analog?

Synopsis

Computational modeling offers substantial potential for investigating the hypothesized biomechanical pathways of VIIP with respect to:

- Changes to IOP/ICP in response to changes in vascular compliance/pressure
- Link between exposure to microgravity and changes to visual acuity, IOP and ICP
- Link between visual acuity and choroidal engorgement, elevated IOP and ICP

Questions?